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EFFECTS OF HIGH POWER LASERS, NUMBER 3

Stuart G. Hibben

Informatics, Incorporated

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This is a compilation of abstracts of Soviet studies on high power lasers technology that were published in the first quarter of 1974. Material on this subject for the previous year has appeared in the monthly Selected Material from Soviet Technical Literature for 1973, now discontinued.

Articles were selected as the most pertinent from the total list of attached bibliographic entries. They are grouped by laser interaction with metals, dielectrics, semiconductors, miscellaneous targets, and laser-plasma interaction.

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INTRODUCTION

This is a compilation of abstracts of Soviet studies on high power laser technology that were published in the first quarter of 1974. Material on this subject for the previous year has appeared in the monthly Selected Material from Soviet Technical Literature for 1973, now discontinued.

Articles were selected as the most pertinent from the total list of attached bibliographic entries. They are grouped by laser interaction with metals, dielectrics, semiconductors, miscellaneous targets, and laser-plasma interaction.

A first-author index and an index of source abbreviations are appended.

TABLE OF CONTENTS

1. Metals

Anisimov, S. I., B. L. Kapeliovich, and T. L. Perel'man. Electron emission from a metal surface induced by ultrashort laser pulses. ZhETF, v. 66, no. 2, 1974, 776-781.

Competitive thermoelectronic and photoelectric mechanisms of emission from a metal surface are studied theoretically, for the case of electron emission induced by the action of picosecond laser pulses. The emission current I and the total charge q emitted from the surface are calculated. In the most general case, thermoelectronic emission current is calculated by solving a set of equations of energy balance and calculating electron temperature θ_e. Numerical solutions for I and θ_e are obtained for a wide range of the parameters δ, μ, and ϵ which are dimensionless functions of I, pulse duration τ, and light absorption coefficient $\varkappa$, respectively.

In the physically most significant case of $\delta < 1$ and $\mu < 1$, calculations show that the time dependence of θ_e practically duplicates laser pulse shape, hence there is no delay of the emission pulse with respect to the laser pulse. This is explained by the very low heat capacity of the degenerate electron gas thermally insulated from the lattice for the duration of the laser pulse. In this case, separate observation of the thermoelectric current delayed with respect to the photoelectric current becomes impossible.

Thermoelectronic emission current is calculated from the Richardson formula for the case of θ_e well below the electron work function. The total charge q_t emitted by the thermoelectronic mechanism is calculated by subsequent integration. In the case of $\delta < 1$ and $\mu < 1$, under typical experimental conditions, q_t is estimated to be $\sim 10^5$ electrons for a reflection coefficient R = 0.8.

The total charge q_p emitted by the multiple quanta photoelectric mechanism is formulated for a triangular pulse of half width τ and a Gaussian distribution of intensity over the beam cross-section. Analysis shows that there is a critical value of the absorbed radiation density (I-R) I_m above which thermoelectronic emission prevails over photoelectric emission. The critical (I-R) I_m for metals was estimated from $q_p = q_t$ to be 10^9-10^{10} w/cm^2. Regardless of the emission mechanism, the study of thermoelectronic emission induced by picosecond laser pulses gives a concept of electron lattice relaxation kinetics.

Rykalin, N. N., A. A. Uglov, and A. N. Kokora. Interaction of high-power CO_2 laser radiation with iron and ferrous alloys. FiKhOM, no. 1, 1974, 3-9.

The experimentally observed effects of a 700 w CO_2 laser beam on Armco iron; type 45, U8 and KhVG steels; and white and grey pig iron in an oxidizing atmosphere (air) are evaluated, to establish basic patterns of the interaction and associated phenomena. In the experiments, a single-mode CO_2 laser beam at 7×10^4 w/cm^2 power density and $\sim 10^{-3}$ rad divergence was focused on polished specimens. The following effects were observed: formation of up to 200 μ deep and 2 mm diameter craters after 5 sec. irradiation; surface vaporization as a significant factor of crater formation; formation of a thick (up to $\sim 150\ \mu$ in the case of iron) oxide film; and redistribution of alloy elements within the interaction region. The process of heating with the resulting formation of a thick oxide film (scale), hydrodynamic phenomena, and mass transfer in the interaction region are analyzed.

Three consecutive phases of heating are distinguished, depending on the surface temperature: an initial phase to $T_o = 300$-400° C, which is attained in time τ_o; the first phase of intensive oxidation to $T < 570^\circ$ C with formation of Fe_3O_4 scale; and the second oxidation phase at $T > 570^\circ$ C with formation of mostly wustite (FeO) scale and an external layer of $Fe_3O_4 + Fe_2O_3$. The kinetics of scale growth is described

in terms of the simplified Wagner diffusion theory. Assuming that only the numerical value of the kinetic coefficients varies with T, the authors describe the growth of thick films approximately by the parabolic equation

$$\ell^2 = K_P \tau \qquad (1)$$

where $K_P = -2k\lambda\Delta C$, λ is the activation energy barrier and ΔC is the difference in defect concentrations at the vapor-oxide and oxide-metal interfaces. Numerical calculation with the use of (1) shows that a $\sim 10^3$ Å film builds up in 10^{-2}--10^{-3} sec, i.e., in a time significantly shorter than the experimental interaction time. After $\tau \sim 10^{-2}$ sec, the thermal problem becomes exceedingly complicated.

The crater depth as evaluated by the thermal failure theory was an order of magnitude higher than the experimental value. This discrepancy is explained as the result of evaluation without taking into account the deformation (deflection) of liquid phase, or losses due to thermal conductivity. Changes in concentration of alloying elements, notably Mn and Cr, was detected along the path of the laser beam in a liquid steel bath, and is attributed to redistribution of the additives in the bath.

It follows that failure of iron and ferrous alloys from the effect of a high-power CO_2 laser beam in air can be described in the framework of ordinary heat theory with allowance for thermal oxidation.

Levinson, G. R., and V. I. Smilga. Destruction mechanism of thin metallic films under focused laser radiation. Kvantovaya Elektronika, no. 3(15), 1973 72-78.

The destruction process of thin metallic films due to laser radiation was experimentally investigated. A pulsed nitrogen laser in the UV

range was used in the experiment with the following parameters: emitted wavelength-337.1 nm, pulse duration -10^{-8} sec, pulsed power - up to 10^4 watt. The experimental setup and procedure are given in a previous work by the authors (FiKhOM, no. 4, 1971, 124).

Specimens tested were Al, Cr, Cu, Ag, Pb opaque films, deposited on a quartz substrate by vacuum evaporation. Data on the process of film destruction were obtained by analyzing the size of holes developed in them, and their surface conditions as functions of power and intensity of laser radiation, and the number of laser pulses. Fig. 1 shows microphotographs of films subjected to laser radiation.

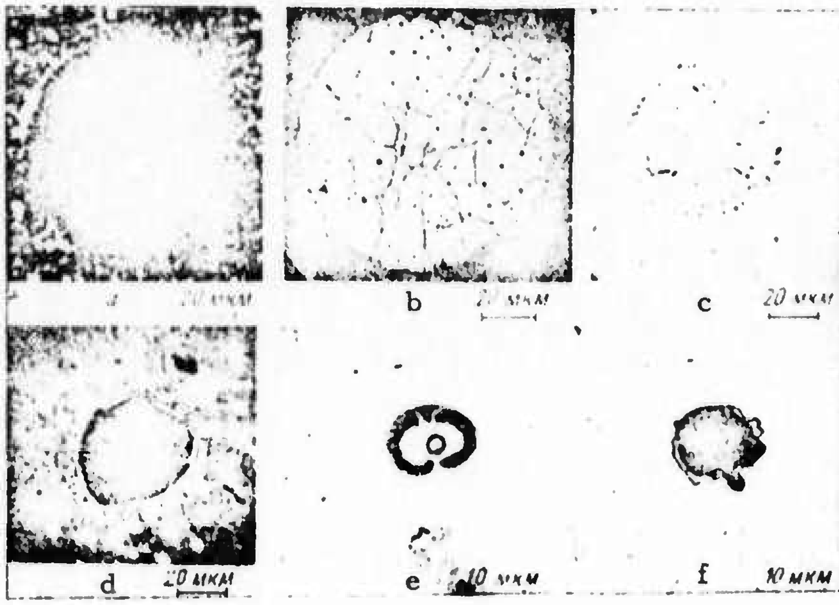


Fig. 1. Microphotographs of films subjected to laser radiation.

a) Pb (320) at subthreshold intensity
b) Cr (500) at subthreshold intensity
c) Al (500) at just over threshold
d) Cr (500), transient layer is visible
e) Cu (1350) at subthreshold intensity after 1 pulse
f) Cu (1350) at subthreshold intensity after 50 pulses.

It was confirmed that the main mechanism of hole formation by laser pulses of short duration was evaporation. Experimental results are compared in detail with those of investigations based on the evaporation model (i.e. presence of two threshold intensities and quantitative relation between them; presence of transient layers; gradual formation of holes at radiation intensity less than 2nd threshold but more than the first; widening of holes during multiple action of the pulse). These are found to be in good agreement.

Samsonov, G. V., A. D. Verkhoturov, V. S. Kovalenko, A. I. Roshchina, V. P. Kotlyarov, and N. I. Prikhod'ko. Estimating erosion of metals and carbides under laser radiation. EOM, no. 6, 1973, 5-8.

Possibilities of using geometric dimensions of holes and gravimetric values of ejected materials from holes were studied, to select criteria for estimating erosion of transition metals and their carbides under laser radiation. Metal specimens of the IV-VI groups (Zn, Zr, Ti, Fe, V, Nb, Hf, Ta, Ni Cr, Re, Mo, W) and their carbides were treated on the SLS-10-1 laser device in air under the following conditions: radiation power - 10 kw, power density - 1.3×10^6 watt/cm^2, pulse duration - 0.0015 sec, wavelength 10600 Å. The focal distance of the optical system was 37 mm; the laser radiation was focused directly onto the specimen surface. Studies were then conducted of the holes generated by single laser pulses. Specimens were weighed before and after laser exposure after which they were cut by electric arc in diametric cross-sections.

It was found that the most reliable criteria for estimating erosion resistance of laser-treated transition metals was the volume of the resulting holes. In the case of carbides, where brittle destruction of the specimen occurs, the most reliable erosion criterion is the gravimetric characteristics of the specimen ejecta.

Arutyunyan, I. N., and G. A. Askar'yan. Coherent r-f radiation from electron emission due to short laser pulses on a metal surface. ZhETF, v. 65, no. 6, 1973, 2214-2216.

The authors examine r-f radiation associated with ejection of electrons by laser emission. It is noted that the generation of short and ultrashort laser pulses ($\tau = 10^{-11} - 10^{-12}$ sec) and the possibility of their further compression or photon contraction down to $\tau = 10^{-13}$ sec. makes it possible to obtain r-f emission of significantly short wave ($\lambda = 0.3$-3 mm at $\tau \sim (1\text{-}10)\times10^{-12}$ sec) from electron emissions, resulting from laser pulses on a metal surface. It is further shown that bursts of short r-f waves can be obtained by spatial modulation of the emission. Expressions are derived for the spatial distribution of the radiation, and its intensity is estimated. The authors point out that on the basis of the r-f radiation spectrum it is possible to assess the shape of the electron bunch generated by picosecond light pulses, as well as the shape of the laser pulse itself.

Lysikov, Yu. I. Evaporation in vacuum of thin metallic films, heated by laser radiation. FiKhOM, no. 6, 1973, 67-71.

The evaporation kinetics is discussed of thin metallic films, deposited on large transparent substrates, obtained from powerful optical radiation in vacuum. Equations are developed for thermal conductivity of the film and gas dynamics of vapor atoms. Hydrodynamic variables are calculated of the vapor layer formed during laser heating of the films. The total time of film evaporation and the resulting recoil momentum transferred to the substrate during evaporation, are determined. It was found that recoil momentum during film evaporation is approximately proportional to the film thickness. In this study, thermal conductivity equations are solved on the assumption that portions of the optical flux not reflected from the film are all absorbed.

Gazuko, I. V., L. L. Krapivin, and L. I. Mirkin. Sintering of powders and chemico-thermal treatment of metal surfaces by laser beam heating. Poroshkovaya metallurgiya, no. 1, 1974, 27-30.

Possibilities are investigated for controlling chemical reactions during the action of a laser beam on a metal surface, and using these reactions for obtaining a saturation layer on the metal surface or for sintering powders. A series of experimental schemes were used for heating a powder layer on a metal surface or combined heating of a powder mixtures by laser pulses (Fig. 1). Irradiation was by a GOS-30M laser with pulse energy up to 30 joules and 10^{-3} sec duration; a single pulse treated a surface area of about 50 mm^2 and thickness of 0.1 mm. Evaluation was done by metallographic and x-ray structural methods with intensity recording by scintillation counters.

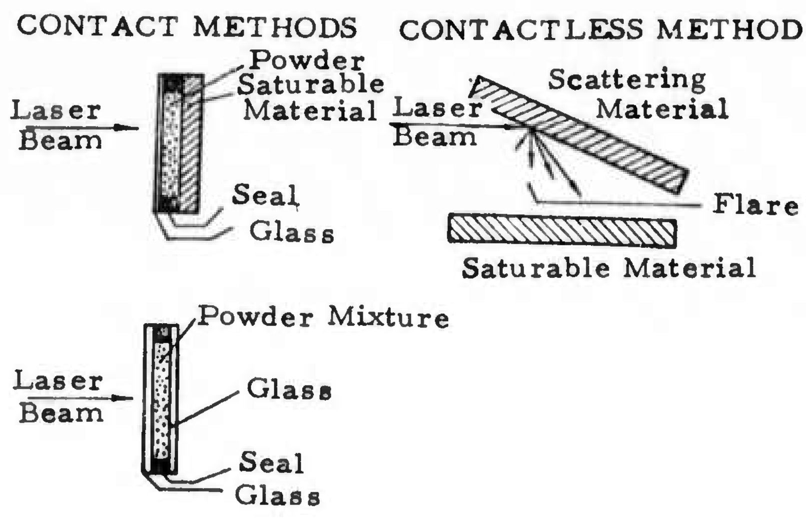


Fig. 1. Experimental schemes of laser beam irradiation of power mixtures and metals covered by powders.

Experiments were conducted with solid solutions (iron-carbon, iron-tungsten, etc), compounds (cobalt-tungsten, aluminum-niobium, iron-silicon, etc) and also simultaneously with solid solutions and chemical compounds. In the case of an iron-tungsten system it was found possible to obtain solid solutions with concentrations exceeding equilibrium by more than 3 times. Possible physical mechanisms are discussed of the observed phenomena.

Kuznetsov, V. A., and A. A. Shchuka. Interaction of laser radiation with a tungsten surface. IN: Sb. Struktura i svoystva monokristallov tugoplavkikh metallov. Moskva, Izd-vo nauka, 1973, 86-92. (RZhMetallurgiya, 1/74, no. 1I310). (Translation)

Desorption of gases from a tungsten surface due to laser radiation was studied by field emission microscopy. A tungsten needle was irradiated by laser pulses after its surface was covered by a single-layer of adsorbed atoms. Field emission current reached 95% of the initial value corresponding to a pure surface. Thus, at laser flux densities below that of surface destruction, the possible desorption equalled ~0.96 of the single-layered adsorbed atoms. A similar investigation was conducted with large tungsten specimens, from which it was seen that local cleaning of the surface was obtained by laser radiation. Distribution of the field emission density was examined along the surface of a tungsten needle at the moment of laser irradiation. Observations showed that the desorption was a result of laser heating of the specimen. The authors conclude that the combined use of a laser beam and field emission microscopy is quite promising for studying the interaction of radiation with a metal surface.

Goryachev, N. L., G. A. Komov, N. L. Korzhikov, and Yu. A. Chervyakov. Increase in hardness and wear resistance of steels from the effect of laser radiation. FiKhOM, no. 2, 1974, 43-49.

Theoretical and experimental data are given on the effect of laser pulse parameters on microhardness and dimensions of hardening range for type R18, ShKh15, KhVG, U10, U12, and 38KhMYuA steels. Theoretical calculations for the depth z of the hardening range were made by means of approximate formulas, derived without imposing limits on the time variable t and assuming irradiation from a free-running laser.

The calculated effects of radiation energy density E on the surface, the pulse duration τ, and the parameter k of the laser active material on z, z(r), and relative radius r/R of the hardening range are illustrated graphically. It is shown that the cumulative effect of a pulse series on temperature is practically negligible. A free-running GOR-100 M laser generating 7 to 80 j pulses with τ = 0.7 and 3 msec was used in the experiments. The experimental microhardness HV of the laser hardened steels was found to be much higher than before irradiation, and was also higher than HV of heat-treated steels. Data obtained in separate experiments show that laser irradiation can significantly increase the wear resistance of KhVG, ShKh 15, 10, and 38KhMYuA steels. The average energy density in these experiments varied from 9 to 46 j/cm^2; in the experiments of HV determination, it was as high as 104 j/cm^2.

Uglov, A. A., and O. I. Stepanova. Method of determining porosity of solids. ZL, no. 1, 1974, 49-51.

A method is suggested for determining porosity of materials by means of the action of laser beam on them. Experimental investigations were conducted with porous specimens of tungsten and molybdenum, using a GOS-30M Nd glass laser. Operating conditions of the laser were: free-running, maximum pulse duration τ = 0.8 millisec., random spiked emission. Energy was varied from 3 to 12 joules by changing pumping energy; flux density was 2×10^6 -- 7.5×10^6 watt/cm^2. Depth of holes formed by laser beam on the specimen was measured by a MIM-7 microscope. Relationships were plotted for the depth of holes as a function of porosity (Fig. 1) and crater diameter (Fig. 2).

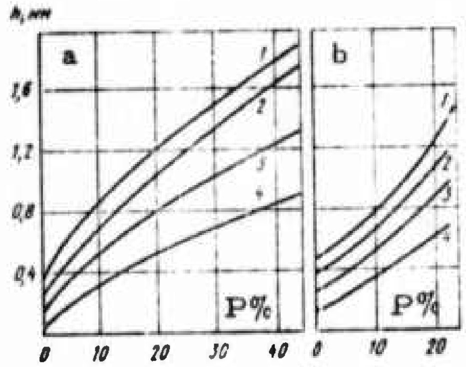


Fig. 1. Crater depth as a function of porosity P for a) tungsten and b) molybdenum at flux densities; 1) - 7.3×10^6, 2) - 6×10^6; 3) - 4.2×10^6; 4) - 2×10^6 watt/cm^2.

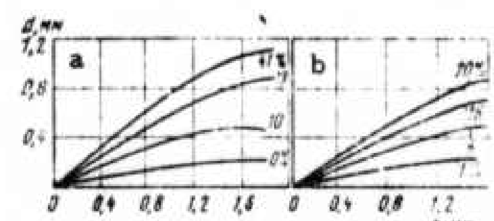


Fig. 2. Crater depth as a function of its diameter at specific porosities of a) tungsten and b) molybdenum.

The authors note that the described method is a relative one and not absolute, but may be used as a quick method for determining porosity of any form of metal. The accuracy of the method depends on the precision of measuring crater depth, and is in the vicinity of 8%. For increasing the accuracy, the authors suggest using laser radiation in a regular pulsed regime.

Bergel'son, V. I., A. P. Golub', I. V. Nemchinov, and S. P. Popov. Plasma formation in vapor layers generated under the action of laser radiation on a solid. Kvantovaya Elektronika, no. 4(16) 1973, 20-27.

The authors undertake numerical solutions of unstable one-dimensional plane gas dynamic problems on scattering of vapors in vacuum, formed from laser pulses on solids. Radiation pulse shapes are assumed arbitrary. The absorption mechanisms considered include collision of electrons with atoms; free transition of electrons in an ion field; and bound-free transitions with a highly excited state of atoms. Equations are derived for vapor motion and thermal conductivity. Distinctions in temperature of electrons and ions (atoms) are taken into account, and heat dissipation from evaporation waves in the interior of the solid due to thermal conductivity is also accounted for.

It is shown that, as in equilibrium conditions, an absorptive flare occurs at sufficiently high radiant flux, i. e. a layer of plasma is formed with an ionization level of the order of unity, which strongly absorbs laser radiation. Table 1 shows calculated results of the action of a neodymium laser on aluminum at pulse durations of 0.52 and 5.2 μsec. It is seen that

Table 1

$\tau_{1/2} = 0.52$ μs					$\tau_{1/2} = 5.2$ μs				
q_{max}, Mw/cm^2	t_v, μs	t_e, μs	q_e, Mw/cm^2	$p_{o\,max}$, bar	q_{max}, Mw/cm^2	t_v, μs	t_e, μs	q_e, Mw/cm^2	$p_{o\,max}$, bar
100	0,30	0,43	79	310	30	3,0	4,5	25	120
80	0,33	0,47	74	290	20	3,6	5,5	20	96
50	0,40	0,64	48	190	15	4,1	7,8	9,4	66
40	0,44	—	—	110	10	4,9	—	—	23

t_v - initial intensive evaporation time (time, when vapor pressure p_W equals 1 bar).
t_e - shielding time (when electron temperature T_{emax} reaches 0.75 ev).
q_e - radiant flux density at the moment of shielding
$p_{o\,max}$ - max. pressure in front of evaporation wave.

The critical flux at which a high-temperature plasma is generated within a given time, decreases with increase in pulse width. According to the authors, this criterion offers the possibility of obtaining plasma at moderate laser intensities on targets for experimental purposes. However, this is true only for significantly large dimensions of beam cross-section.

At $t_e - t_v = 0.1 - 0.2$ μsec and vapor discharge velocity = 2 km/sec, the characteristic vapor layer thickness x_e at the shielding moment equals 0.2 - 0.4 mm. At $t_e - t_v = 1.5 - 3$ μsec, $x_e = 3\text{-}6$ mm correspondingly. The authors point out that the diameter of the irradiated spot should be more than the value of x_e, so that effects of the lateral flow of vapor jets can be neglected during generation of a strongly ionized plasma over the target surface.

Annenkov, V. D., A. I. Barchukov, Yu. I. Davydov, et al. Investigating structures of steel and cast iron in the interaction zone of continuous laser radiation. FiKhOM, no. 2, 1974, 38-42.

Structures of steel and cast iron were experimentally investigated after exposure to continuous focused CO_2 laser radiation for periods from tenths of seconds to several seconds. Experiments were conducted with a single-mode laser generating up to 700 watts. The beam was focused on specimens by an NaCl lens with f = 170 mm; divergence was about 10^{-3} rad. Power density without allowing for reflection was about 7×10^4 watt/cm^2.

Specimens studied were type 45, U8, and KhVG steels, and gray and white cast iron. Irradiation of the specimens for a period of 5 sec developed craters of diameter = 1.5-1.8 mm and depths up to 0.2 mm, depending on the duration of interaction. Uneven cylindrical metal particles were observed to form around crater perimeters over the specimen surface; their dimensions did not exceed some 0.3 mm. The craters also showed concentric zones of different colors, with the outermost bands of up to 6--8 mm diameter being the darkest. The volume of the craters was significantly greater than that of the cylindrical particles together with the volume of sputtered droplets; this confirms the evaporation and ejection of a significant portion of metal from the craters. Microstructures of crater regions were studied by viewing thin sections, taken perpendicular to the crater axis. Structural changes resulting from irradiation for 5 sec are discussed in detail. A number of magnified photos showing crater formation and structural changes are included.

2. Dielectrics

Zhbankov, R. G., V. A. Zhdanovskiy, L. I. Kiselevskiy, V. N. Snopko, and S. P. Firsov. Effect of monochromatic radiation on the change in physical structure of polymers. ZhPS, v. 20, no. 2, 1974, 317-319.

Changes in the physical structure of polymers due to monochromatic radiation were experimentally investigated. Triacetate film specimens of different thickness (25-75 μ) were subjected to CO_2 laser radiation, operating in a c-w mode. The laser beam was normal to the specimen surface; energy density was varied by offsetting the specimen different distances from the focal plane. The cross-section of the specimen surface thus treated was 1-2 cm^2, incident flux density - up to 300 watt/cm^2, and time of exposure was 0.02 to 1 sec.

It was found that laser irradiation of triacetate films led to a sharply accelerated appearance in spectroscopic indications of crystallization, as compared to their treatment by thermal radiation. For example, minimum time necessary for the appearance of crystallization from thermal treatment under laboratory conditions was 0.5 - 5 min, while with laser radiation the required time was only 0.02 - 1 sec. The power densities of incident radiation at minimum irradiation time (for a constant film thickness 75 μm) were approximately of similar values (4.5 - 6 joule/cm^2, Table 1). During crystallization by thermal treatment (T = 200 - 210° C), the

Table 1

Energetic flux density of laser radiation and corresponding min. time of irradiation for triacetate films, required for the appearance of crystallization.

W, w/cm^2	300	90	48	9	5
t_{min}, sec	0,02	0,06	0,12	0,5	1
E, j/cm^2	6	5,4	5,8	4,5	5

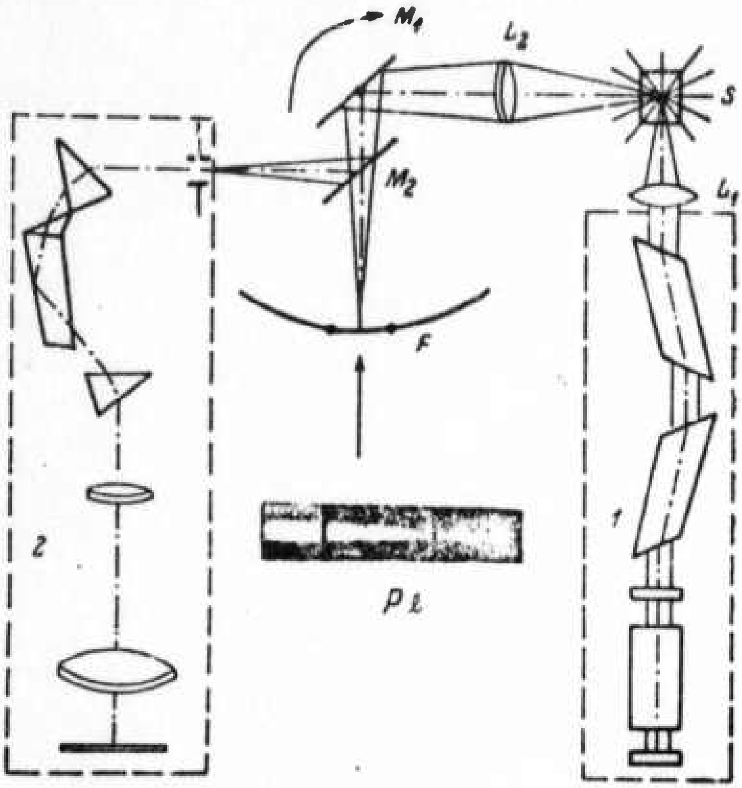
film was subjected to a flux density ~0.3 watt/cm^2. Energy falling on a 1 cm^2 film surface in this case was 18 - 180 joules for 30 - 300 sec, which significantly exceeds the energy needed for crystallization by laser radiation.

The authors conclude that under the conditions of the cited experiments, selective localization of absorbed radiant energy takes place in structural-active bands. Further refinements in testing are needed to verify the particular characteristics of the laser mode of film crystallization.

Arkhipov, Yu. V., N. V. Morachev, V. V. Morozov, and F. S. Fayzullov. Spectral characteristics of illumination, arising from destruction of transparent dielectrics by laser radiation. FTT, no. 1, 1974, 71-76.

Spectrophotometric investigations were conducted of illumination, associated with the destruction of transparent dielectrics under laser radiation. The experimental sketch is shown in Fig. 1. Tests were done with a glass laser, operating in free-running regime with two-stage amplification. Maximum radiation energy was 400 joules at pulse duration ~10^{-3} sec; beam divergence was 5 x 10^{-3} rad and resolving time ~100 nsec. Incident intensity ~(0.5-1)x10^8 watt/cm^2. Materials investigated were K-8 optical glass synthetic and fused quartz. Laser radiation was focused by a lens, f = 15 cm both inside the test specimen and on its surface.

Fig. 2 show a spectrogram of radiation resulting from internal destruction of fused quartz and its calculated results in the form of relative intensity distribution (initial stage). Temperatures of the luminous regions were determined from the distribution of relative intensities



1 - Nd glass laser;
2 - Spectrograph;
L_1 - Focusing lens;
L_2 - Objective;
S - Specimen;
M_1 - Rotating mirror
M_2 - Splitter;
F - Cassette of SFR-2M camera
Pl - Image of the luminous region

Fig. 1. Sketch of experimental setup.

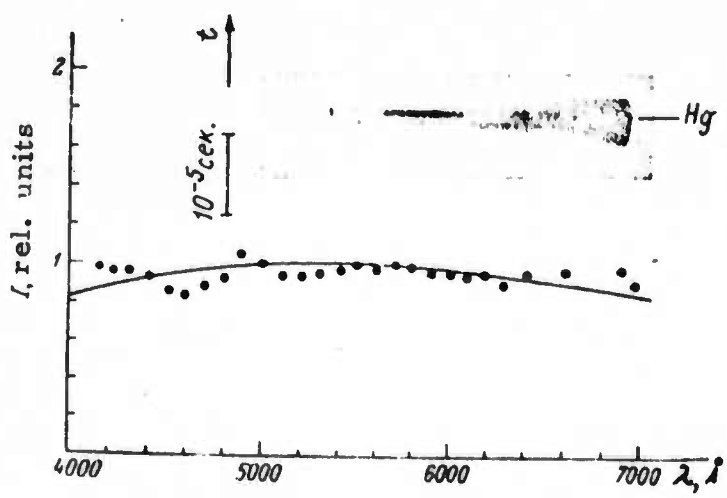


Fig. 2. Relative spectral intensity of radiation resulting from internal destruction of fused quartz. (Line - distribution in black body spectrum at T = 55×10^3 °K. Top - corresponding spectrogram).

in the illumination spectra; internally those are (5-7) x 10^3 °K, and on the surface - (2-2.5) x 10^4 °K. High-speed photographs were also taken of luminous regions to obtain information on the spatial development of internal destruction. It was found that destruction in its initial stage takes the form of individual cracks of dimension ≤ 0.1 cm, which were generated sequentially during 10-30 μsec.

Experiments were conducted at ambient conditions as well as in vacuum at 10^{-2} torr. Spectrograms of illumination and calculated results in the form of relative intensity distribution in vacuum for fused quartz are shown in Fig. 3.

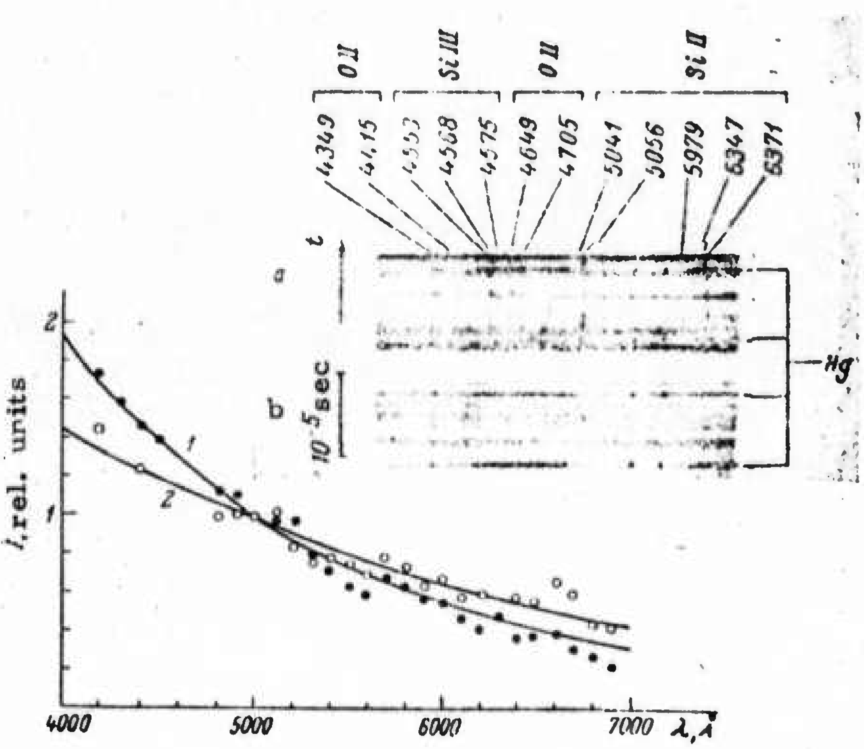


Fig. 3. Relative spectral radiation intensities of the flare (a) and crater (b), resulting from surface destruction of fused quartz. (Curves-distribution in black body spectra: 1) - 2x10^4 °K, 2) - 10^4 °K.

A discussion is given on the kinetics of laser radiation absorption on the surface and internally in transparent dielectrics.

Makshantsev, B. I., A. A. Kovalev, R. K. Leonov, and P. A. Yampol'skiy. Nonradiative electron transitions and thermal effects in transparent dielectrics due to laser pulses. ZhTF, no. 1, 1974, 164-172.

The present work considers a model of laser radiation interaction with transparent crystalline dielectrics. It is assumed that a small portion of the impurity centers, strongly absorbing laser radiation, occur in bunches. Heating of these bunches takes place under laser radiation owing to nonradiative electron transitions in the impurity centers; the conversion of absorbed energy into heat is assumed to be exponentially dependent on temperature.

The authors show that if the number of impurity centers in a bunch, n, is less than a certain value n_o, the temperature in the bunch is low (less than 400^oK) at any intensity of incident radiation. If however $n > n_o$, then strong heating of the bunch up to $T = 10^4\ ^oK$ is possible at certain intensities of laser radiation. At the condition $n_o < n < (4/e)^{3/2} n_o$, where e = electron charge, the steady-state temperature T as a function of intensity I undergoes an abrupt change at some $I = I_{crit.}$ Expressions are also derived for the number of conduction electrons generated by laser pulses in a transparent dielectric.

Based on the obtained results, the authors also analyze the behavior of photocurrent and its dependence on laser radiation intensity in crystalline quartz. If the dielectric mainly contains bunches with the number

of impurity centers sufficiently close to n_o, the dependence of photocurrent on intensity would undergo an abrupt change at $I = I_{crit}$, similar to the temperature in the bunch.

The authors point out that the above considerations for transparent crystals can be applied as well to noncrystalline transparent dielectrics without any substantial changes, if it is assumed that the latter contain significantly large regions of crystallinity with impurity centers as discussed above.

Agranat, M. B., N. P. Novikov, V. P. Perminov, and P. A. Yampol'skiy. Dependence of the threshold values of laser pulses for plexiglass on specimen temperature and tensile stress. MP, no. 6, 1973, 997-1000.

Based on the mechanism of gas formation during interaction of laser radiation with transparent polymers, a discussion is given of certain characteristics of this process. Experiments were performed to determine the temperature regimes of gas formation. Measurements were taken of threshold pulses (I_p, E_p) for specimens at different temperatures. During exposure, specimens were placed in two types of special heating chambers; in both cases the laser action was identical. Specimens were cooled in a liquid nitrogen Dewar, having a flat window for admitting laser radiation. Results are shown in Table 1. It is seen from the table that I_p is practically independent of specimen threshold temperature up to the softening point.

A second set of experiments was conducted to find the difference in values of threshold destruction pulses between Q-switched and free-running (millisecond) regimes. Specimens exposed to the laser were kept in stress at different tensions up to $0.9\sigma_p$, where σ_p - rupture stress.

Table 1

PMMA		PS	
T, °C	I_{pT}/I_p 20° C	T, °C	I_{pT}/I_p 20° C
−190	1,0	−190	1,0
0	0,9	0	1,0
20	1,0	20	1,0
80	1,1	80	1,1
100	1,0	100	1,0
150	0,9	150	0,9
200	0,3	180	0,2

$\lambda = 1{,}06$ мкм; $\tau = 4 \cdot 10^{-8}$ sec.

Results of these experiments, i. e. dependence of I_p nanosecond pulses and E_p millisecond pulses on tensile strength σ, are given in Table 2.

Table 2

σ/σ_p	$I_{p\sigma}/I_{p0}$ $\tau = 4 \cdot 10^{-8}$ сек	$E_{p\sigma}/E_{p0}$ $\tau = 10^{-3}$ сек
0	1,0	1,0
0,4	1,0	1,0
0,7	1,0	1,15
0,85	1,15	1,35
0,9	1,05	—

$\lambda = 0{,}69$.

It is seen that I_p (nanosecond pulses) is independent of σ. In the case of millisecond pulses, E_p decreases with increase in σ, beginning from $\sigma = 0.7\ \sigma_p$ and at $\sigma = 0.9\ \sigma_p$, millisecond pulses result in specimen destruction, so the threshold values of laser pulses cannot be determined.

These experiments showed that the gas formation process should commence at temperatures about 10^3 °K, and possibly multiphoton processes of photo-destruction would take place in them. However, it is noted that the mechanisms of thermal destruction and multiphoton photodestruction are not the only processes causing gas formation from the action of laser pulses.

Aleshin, I. V., A. M. Bonch-Bruyevich, V. I. Zinchenko, Ya. A. Imas, and V. L. Komolov. Effect of absorbing inhomogeneity distributions on the development of optical breakdown in transparent dielectrics within the limits of the irradiated spot. ZhTF, no. 12, 1973, 2625-2629.

Based on a statistical model for optical breakdown threshold of transparent dielectrics, the authors derive relationships for the threshold as a function of the cross-section of the irradiated spot during focusing of laser radiation on a dielectric surface. Expressions are derived which correlate threshold flux density q with the cross-section of irradiated spot, s; Fig. 1 shows calculated and experimental results.

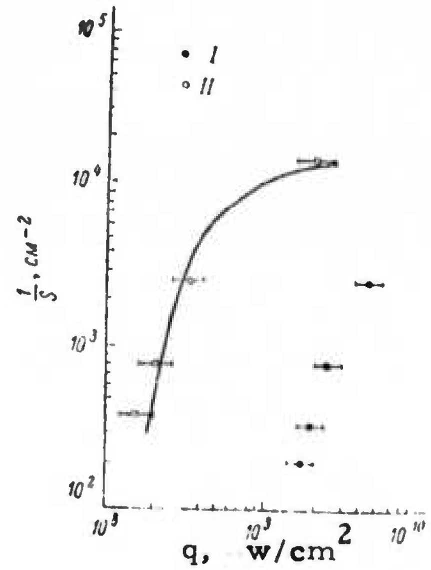


Fig. 1. Dimensional relationship of the threshold optical breakdown of a K-8 glass surface. 1- First regime (t_n = 150 nsec), 2 - Second regime (t_n = 10 μsec). Curve = calculated results.

Experiments were conducted with type K-8 silicon glass as shown in Fig. 2. Irradiation was with a single-mode laser with unstable

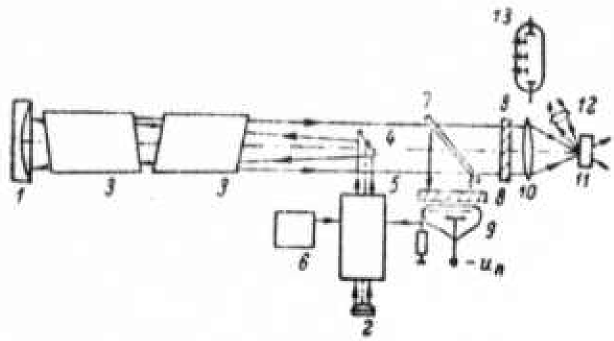


Fig. 2. Sketch of Experiments

1 & 2- resonator mirrors; 3- active elements; 4- rotating prism; 5- modulator; 6- displacement source; 7- beam splitter; 8- calibrated optical wedge; 9- control photoelement, FEK-14; 10- objective; 11- specimen; 12- focusing system for FEU; 13- photomultiplier.

resonator, electro-optical modulator and photoelectric feedback circuit. The laser operated in four regimes, parameters of which are given in Table 1. Threshold optical breakdown of the specimen target surface

Table 1

Operating Conditions	Pulse duration, μsec	Energy, joule	Divergence, sec.
1) Single pulse	0.45	4	30-40
2) Quasicontinuous pulse	10 450	15 150	30-40 40-50
3) Chaotic spike generation	1000	1000	20-30

was identified by the moment of plasma flare formation, using a photo-multiplier. It was found that the optical breakdown threshold increased with decrease of the irradiated spot, for all four operating regimes of the laser. It is seen from Fig. 1 that experimental and calculated results are in good agreement within the tested range.

Ashmarin, I. I., Yu. A. Bykovskiy, V. A. Gridin, et al. Early development stage of laser destruction in glass. FTT, no. 1, 1974, 246-248.

The generation and effect of shock waves were studied, resulting from focusing of laser radiation in a transparent dielectric volume. The shock wave action was investigated at early stages, when the wave was not yet detached from the destruction region (t $\leq$ 30 nsec). The damage and associated shock wave were holographically recorded by a shortened pulse passing through the destruction region during its formation.

A ruby laser pulse of 10 nsec duration and maximum energy of 1.5 joules was focused on a K-8 glass specimen by a lens with f = 36 mm. Time characteristics were determined for the destruction radius (in lateral cross-section) and the shock wave front (Fig. 1). The average radial growth

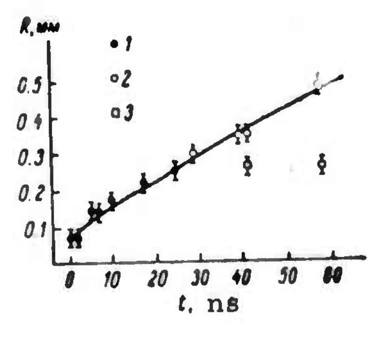


Fig. 1. Time characteristics of destruction radius (in lateral cross-section) and shock wave front.

1) Radius of shock wave front before its separation from damage region; 2) shock wave front radius after separation from damage region; 3) destruction radius (Solid line represents the theoretical behavior of a shock wave front).

rate of destruction equalled $\sim 9 \times 10^5$ cm/sec, which is significantly more than linear sound velocity (5.7×10^5 cm/sec for K-8 glass). At the moment t = 25 nsec, the wave was observed to separate from the damage region and propagate into the substance at a supersonic velocity. The destruction at this moment had a radius which exceeded by more than 2 times the radius of lens curvature in the corresponding cross-section. After this the destruction area did not increase further.

Relationships were determined for the pressure behind the shock wave, shock wave velocity, and specific volume in the rarefaction wave as functions of the initial pressure due to energy release (Fig. 2).

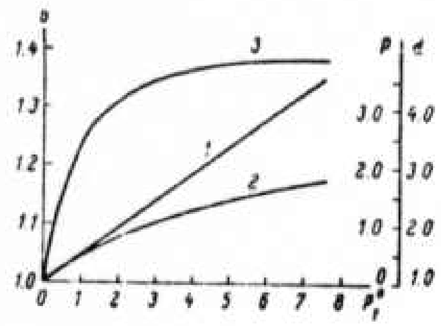


Fig. 2. Relationships of pressure behind shock wave, P(1), shock wave velocity d (2) and specific volume v (3) as a function of initial pressure P_T^o.

For a measured shock wave velocity of 9×10^5 cm/sec, initial pressure was 1.7×10^3 kbar, pressure behind the shock wave = 8.1×10^2 kbar, and the effective volume of energy absorption $V_E = 1.9 \times 10^{-5}$ cm^3. The net volume in which the initial destruction not connected with shock wave was formed equalled 5.5×10^{-5} cm^3.

Volkova, N. V. Effect of shortwave absorption on the destruction threshold of optical crystals by optical radiation. FTT, no. 1, 1974, 307-309.

Correlations of the threshold optical stability of fluorite specimens with their optical transmissibility in the UV spectral region have been established in a study by N. V. Volkova, G. P. Gusev, et al (OMP, in print). The present work extends the established relationship for a wide range of optical crystals. Experiments were conducted with several crystals of different optical properties - LiF, quartz, KDP, calcite and CsI, using several varieties of each with different dissolved impurities. In the experiments, crystal samples were selected as strictly conforming to the following criteria: 1) presence of identical light transmission at the laser radiation wavelength, $\lambda = 0.69\ \mu$; and 2) absence of structural defects (opaque impurities, scattering centers, etc), which affect the threshold optical stability. Destruction of the samples was done by ruby laser radiation operating in a Q-switched regime.

The threshold optical stability for each crystal was determined, using specimens having significantly different light transmission in the shortwave spectral region up to $0.4\ \mu$. LiF and CsI specimens were irradiated along the [001] direction, and quartz, calcite and KDP - in a direction perpendicular to the optical axis. Experimental results are shown in the table. It is seen that for all specimens tested, correlations exist between the threshold destruction of specimens by radiation of wave length 0.69μ and their light transmission at wavelengths below 0.4μ. The presence of shortwave absorption in different crystals hence lowers their optical stability.

Spectral light transmissibility T and energetic threshold optical stability E_{thr}.

Crystal	Specimen No.	T, % (at 1 cm thickness) I	II	III	IV	E_{thr}, joule/cm^2
LiF	1	80	90	93	93	180
	2	50	80	92	93	20
	3	74	88	93	93	18
Quartz	1	88	95	95	95	300
	2	70	87	94	95	80
KDP	1	60	86	92	92	100
	2	40	80	92	92	35
$CaCO_3$	1	60	90	96	96	630
	2	30	20	82	96	80
	3	0	12	70	96	40
	4	50	80	96	96	35
CsI	1	0	65	75	80	30
	2	0	50	75	80	10

λ, μ: I — 0.2, II — 0.3, III — 0.4, IV — 0.69.

Makshantsev, B. I., P. S. Kondratenko, and G. M. Gandel'man. Role of absorbing inhomogeneities in cumulative ionization development. FTT, no. 1, 1974, 173-179.

This article undertakes a theoretical study of unstable processes of electron cloud formation around an absorbing inhomogeneity in a transparent dielectric under the action of laser pulses. During laser irradiation, a strong local heating up to temperatures $T \sim 10^4$ °K is produced in the substance. The authors point out that at such temperatures of the inhomogeneity, destruction of the material does not take place owing to the fact that a significant part of the material around the inhomogeneity quickly melts away,

and the phase boundary which is the only place where destruction could occur, remains at the melting point, which is not enough for destruction. This heating produces thermal ionization of the substance, resulting in additional light absorption by free electrons. The electron cloud thus formed may be unstable in relation to its development in the space around the inhomogeneity.

The process of electron cloud formation is treated in detail, for the cases of both strongly absorbing and transparent inhomogeneities. Analytical expressions are derived for instability development time (induction time). It is shown from numerical calculations that the discussed mechanism of electron cloud formation is possibly a cumulative ionization process.

3. Semiconductors

Anisimov, S. I., and V. L. Komolov. Optical breakdown of a compensated semiconductor. FTT, no. 2, 1974, 575-576.

The authors analyze the problem of breakdown of fully compensated semiconductors under the action of light pulses with frequency $\omega < E_g/h$ (E_g - forbidden zone width). Compensated semiconductors are defined as optically inhomogeneous substances, in which fluctuations in dopants create regions of increased absorption, i.e. electron and hole droplets. The optical breakdown mechanism of such semiconductors is a thermal type, initiated by electron droplets as already discussed in a previous work by Anisimov and Makshantsev (FTT, no. 15, 1973, 1090).

The threshold breakdown during focusing of radiation within the specimen is governed by the size of the largest droplets falling within the focal region. This value of threshold breakdown is therefore a random one since droplets of different size are distributed randomly in the specimen. It is noted that the practical approach to determining threshold optical breakdown here is to determine the breakdown probability at given intensity and focusing conditions, instead of seeking a discrete threshold value of intensity. Expressions are derived for determining the breakdown probability of compensated semiconductors as a function of the light intensity in the laser pulse. The authors point out that this approach can also be used for studying breakdown of amorphous semiconductors and glasses.

Ivanov, L. I., N. A. Makhlin, Z. I. Merokh, and V. A. Yanushkevich. Proton diffraction study of a germanium single crystal surface after exposure to radiation of a Q-switched laser. FiKhOM, no. 1, 1974, 30-32.

Surface defects produced simultaneously with internal point defects in Ge single crystals by irradiation with giant pulses from a ruby laser were studied, using a proton diffraction technique based on the blocking effect. The purpose of the study was to evaluate the contribution of the thin laser-produced surface layer with a strongly disordered structure to the resultant change in bulk crystal properties. To do this, a 25 to 140 keV proton beam was focused by means of a coaxial gas laser beam, onto a laser-treated surface area of about 1 mm diam. The diameter of the collimated proton beam was 150 μ. The depth d of the layer with a strongly disordered structure was determined by photometry of the axial shadow image formed by proton passage through the layer to the scattering point and back to the surface. The intensity of the shadow image of scattered protons is greatly decreased, if the d value is significant with respect to the proton mean free path; the shadow image disappears, if the total scattering path is within the layer.

The geometry of proton propagation in the target material shows that the shadow image disappears first in the area where the angle φ is wide (Fig. 1). Depth d is calculated, with allowance for scattering geometry, as

$$d = 2\sqrt{E_0}/k[\sec\alpha - \sec(\theta+\alpha)] \quad (1),$$

where k is a factor in the Lindhard-Scharff equation of energy loss. At 25-100 keV initial proton energy E_0, d was found to be 2×10^{-5} cm. Hence formation of a thin (~2,000Å) quasiamorphous layer on the crystal surface

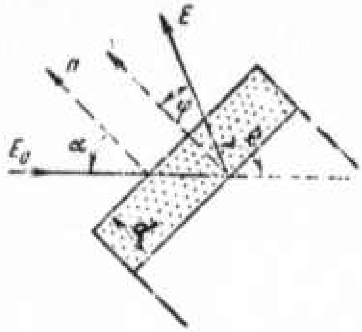


Fig. 1. Trajectory of protons forming shadow image: α - angle of incidence, θ - scattering angle, φ - angle between exit direction of scattered protons and the normal to the surface.

resulted from the action of giant laser pulses. This layer is much thinner than the layer below it. The lower layer has a high concentration of point defects which affect electrical properties of metals and semiconductors.

4. Miscellaneous Studies

Askar'yan, G. A., Ye. K. Karlova, R. P. Petrov, and V. B. Studenov. Action of powerful laser beam on the surface of water with a liquid film. Selective evaporation, burning and blowout of a layer covering the water surface. ZhETF P, v. 18, no. 11, 1973, 665-667.

Evaporation, burning and blowout of a liquid film (kerosene, petroleum, oil) on a water surface was experimentally studied under the action of powerful infrared CO_2 laser in pulsed and c-w regimes at $\lambda = 10\mu$. The laser beam was directed on a water surface covered by a film of the test liquid; the beam of 10 mm diameter was focused by a lens (f = 30 cm) into a spot of radius r = 1 mm ($r = F\varphi$ where angle of divergence $\varphi = 2 \times 10^{-3}$ rad). A convectional upwelling of the beam-heated water was observed at the surface, which led to surface swelling and repulsion of the surface layer. Owing to this process, it was found that a linear beam track on the liquid surface tended to confine the flow and give rise to surface evaporation of the film along the confinement perimeter.

The authors suggest that the observed effects could be used for beamed cleaning of liquid surfaces e. g. dirty surface waters of the sea, rivers and lakes with petroleum products. This effect of local heating and film burning could also be used in laboratories for illumination, Q-switching, modulation of reflection and transmission, among others. It is noted that besides laser radiation, powerful electromagnetic radiation at centimeter, millimeter and submillimeter wavelengths could also be used for heating of the water surface.

Krokhin, O. N., F. A. Nikolayev, and G. B. Sklizkov. <u>Possibility of measuring density in the compression region of a laser thermonuclear target by nuclear physics methods.</u> ZhETF P, v. 19, no. 6, 1974, 389-391.

Based on the recording of positron annihilation events in the nucleus of a super-compressed target, possibilities are discussed of the diagnostics of superdense plasma ($n > 10^{23}$ cm^{-3}), compressed by laser radiation. A possible variant of an experimental scheme for measuring density is shown in Fig. 1. Measurement of positron lifetime $\sim 10^{-12}$ sec,

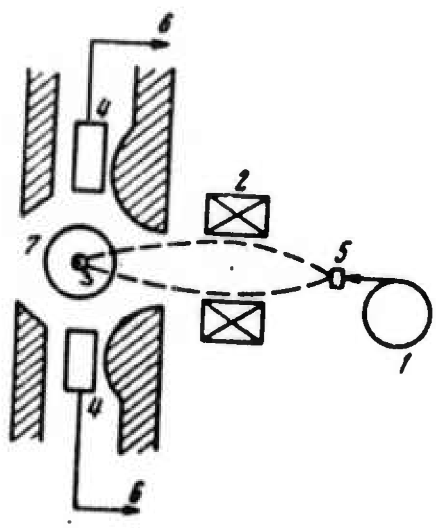


Fig. 1. Experimental Sketch.

1- battery; 2- focusing system; 3- spherical target heated by laser; 4- γ-radiation detectors; 5- target-converter; 6- to coincidence circuit; 7- thermonuclear chamber.

which corresponds to a compression $\sim 10^2$-10^3, although possible in principle, requires the use of complex techniques in measuring picosecond pulses. However, there are much simpler and effective methods, based on the fact that if positron concentration in the target is kept constant throughout an interval exceeding the time of the compression process ($\sim 10^{-9}$ sec), then during the sharp increase of density in the compression region, fast annihilation takes place of almost all positrons thermolysed in the target; it follows that the relation of the number of annihilation events in the compressed and normal states gives directly the value of compression ρ/ρ_0. Conclusions are:

1. Measurement of the total number of annihilation events during existence of a dense target nucleus enables one to determine the mass of compression region, but in this case, it is necessary to know the absolute value of incident positron flux and its energetic spectrum.

2. It is possible to use photodisintegration of deuterons for diagnostics of high compression regions of photonuclear reactions. Photonuclear reactions, specially the reactions (γ, n), could be used effectively in the study of targets made of heavy elements or targets with heavy shells.

Alekseyev, V. N., Yu. A. Anan'yev, and E. F. Dauengauer. Powerful solid-state lasers with telescopic resonators. DAN SSSR, v. 214, no. 3, 1974, 535-538.

Telescopic resonators for decreasing angular divergence of solid laser radiation have been in use for some time; however, material published to date on this topic relate only to generators with comparatively low energetic characteristics. The present work deals with lasers having a relatively high specific energy yield (more than 4 joules/cm^3 per pulse). The discussion summarizes a number of previous works, directed towards the perfection of solid-state generators with traditional active elements of circular cross-section. Prospects are discussed for further improving the characteristics of free-running solid lasers.

The active element used in the present experiment was a Nd glass rod of 45 mm diameter and length = 620 mm with a passive absorption coefficient at the operating wavelength of 10^{-3}/cm. A highly effective four-flashlamp system was used for pumping, which secured a satisfactory uniformity in specimen illumination. Each of the four type IFP-20000 lamps was fed by an optimum shaped pulse of duration ~5 nsec and energy ~40 kj. The energy output of the generator with single resonator was 5000 joule and angular divergence Φ decreased to 30"-40"; half of the radiant energy, 4500 joule in this case, was found to concentrate within an aperture angle less than 2'. Other parameters of the telescopic resonator were: amplification factor M = 2, distance between mirrors ~1 m. Similar experiments were also conducted with generators having two heads, placed successively in a common telescopic resonator with M = 5 and base ~2 m. At an energy output of about 8000 joules, angular radiation divergence was found still lower than that with one head.

The results thus showed that the use of telescopic resonators is highly effective for decreasing angular radiation divergence of generators with high sensitivity and high energy output. However, the authors point out that the main problem lies in deformation of the resonator itself due to thermal effects. Further improvement in characteristics of such solid-state lasers hence depends mainly on eliminating (or decreasing) the thermal deformation of the resonators. Two methods for achieving this are suggested: 1) transmission of the beam through the active element obliquely to its side surfaces, such that the beam undergoes several total internal reflections in them; and 2) selection of matching matrix compositions of a glass laser. Both of these methods require that the glass rods used should be rectangular in cross-section. According to the authors, use of rectangular rods, combined with corresponding technological developments, is the most hopeful factor for further improvement of free-running solid lasers.

Panin, M. I., Ye. B. Vinokurova, L. B.-M. Chobanyan, and V. K. Astreinov. Rock demolition by powerful optical radiation. IVUZ Gornyy zhurnal, no. 2, 1974, 61-64.

Results of an experimental demolition of granite from the effect of a laser beam in different atmospheres are given and interpreted in terms of the physiological effects on the human organism and danger of explosion. The c-w laser used emitted 9, 35, and 56% of total radiation in U.V., visible, and IR spectral regions, respectively. The average power density was 0.6 kw/cm^2 focused on a 1 cm^2 area. Irradiation time was up to 10 min, and specimen temperatures attained 2,400° C.

Formation of noxious or dangerous products was monitored by mass spectrometry of atmospheric probes taken immediately after radiation cut-off. Formation of NO was thus detected in the experiment in air, which indicated that there is a real danger resulting from combination of NO with ozone (undetected). In vacuum, CO and N_2 to 300° C, SO_2, NO_2, and F to 1,000° C were detected. At a rock temperature over 1000° C breakdown of organic fragments continued and volatilization of the alkali metal oxide sets in. In the 1,300-1,400° C and 1,500-1,600° C ranges, CN, C_2N_2 and NO appear in the decomposition products of organic fragments. At 1,400-1,470° C, Na^+ and O contents increase simultaneously. Also at 1,400° C, K^+ and NaO contents increase sharply. At 1,800° C, Na-O and K-O compounds are detected.

It is concluded that during rock, specifically granite, demolition at 1,400-1,900° C, eye-irritating alkaline Na and K compounds are given off. The possibility of an explosion is connected with formation of oxidizers, e.g., Na_2O_2, NaO_2, KO_2, BaO_2, PbO_2, MnO_2, O_3, N_2O_5, etc; the interaction of Si, Al, Fe, Ca, Na, and K ultrafine particles with oxygen and nitrogen; and the formation of explosive alkali and alkaline earth metal compounds, e.g., K_3N, Pb_3N, LiSi, Li_4Si, NaSi, KSi, PbSi, or CaSi.

Conditions promoting formation of the cited compounds are discussed and specific safety measures during rock demolition by laser radiation are recommended.

Work in vacuum is the least dangerous. In an oxygen atmosphere unstable oxides present a grave danger. In an inert gas atmosphere, simultaneous accumulation of an ultra fine dust of elements and oxygen is the most dangerous. The dangers of poisoning and explosion depend on intensity and characteristics of rock demolition, i.e., on the laser regime. The cited dangers can be minimized by decreasing the intensity of material vaporization, so that the destruction mechanism is that of cracking or melting.

5. Beam-Plasma Interaction

Al'terkop, B. A., Ye. V. Mishin, and A. A. Rukhadze. Theory of magnetic instability of a laser plasma. ZhETF P, v. 19, no. 5, 1974, 291-294.

A rigorous solution is presented to the problem of magnetic instability of a one-dimensional, inhomogeneous laser plasma. The solution is derived from two hydrodynamic equations which describe small perturbations of the initial stationary state of an inhomogeneous plasma, with allowance for the electron thermal diffusivity $\chi = T_{\omega} \tau / m$. The solution in an x-z coordinate system shows that the χ rate u ($\partial / \partial x$) $\geq \Gamma$, the instability increment; that is, the instability is convective (drift), not absolute by nature.

In contrast to the earlier conclusions of Bol'shov, et al (op. cit., 288) and two of the authors (Phys. Lett, in print), the present solution indicates that perturbation development in the most general case is not exponential, but depends essentially on density and temperature profiles. Only in the particular case of k_n = log n_o = const is this development exponential.

It also follows fromthe presented analysis that in general, magnetic field amplification in an inhomogeneous dense plasma layer is not exponential. The magnetic field attains its maximum value at the layer periphery, where plasma density is minimum. At the periphery, the magnetic field can be more than two orders of magnitude stronger than within the plasma layer, with the plasma density varying by one order. In a laser plasma, for example, a 1 kgs magnetic field can develop on account of a slight ($\leq$ 1 %) nonparallelism between the density and temperature gradients, or on account of the initial temperature fluctuations $\delta T / T_o = 10^{-2}$-10^{-3}.

Bol'shov, L. A., Yu. A. Dreyzin, and A. M. Dykhne. Spontaneous magnetization of electron thermal conductivity in laser plasma. ZhETF P, v. 19, no. 5, 1974, 288-291.

Mechanisms for self-generation of a field in a laser plasma are analyzed. It is shown theoretically that a magnetic field can be generated by external forces in a plasma with density $n \sim 10^{22}$-10^{23} cm^{-3}, electron temperature $T_e = 5$ keV, dimension $a \sim 10^{-2}$ cm. and dispersion time $t_{in} \sim 10^{-9}$ sec. At an angle of the order of unity between the density and temperature gradients $\nabla \log n$ and ∇T_e, the magnetic field in the plasma can grow spontaneously to 10 Mgs during dispersion.

Magnetic field generation and growth are analyzed on the assumption that the field is generated from the effect of thermal emf in an inhomogeneous plasma. To determine magnetization of the electron thermal conductivity requires joint solution of the equations of thermal conductivity and magnetic field generation. A set of equations is accordingly derived to describe, under specified conditions, the evolution of magnetic field B and electron temperature T_e with allowance for the thermal emf, R_T. Numerical solution of the cited equations in the simplest, two-dimensional case shows that drift of B is a function of heat flow, q. The rate of the thermal drift is greater than hydrodynamic velocity at $\ell/a > m/M$, where ℓ is the electron mean free path.

The effect of magnetic fields on spherical compression of a target by a laser pulse is discussed. The presence of a magnetic field with $\Omega_e \tau_e = 1$ may generate plasma instability owing to a breakdown of spherical symmetry of the thermal system; the mechanism of such instability is described. The increment Γ of thermo-magnetic instability is formulated. In the presence of a magnetic field with $\Omega_e \tau_e > 1$, Γ changes sign and perturbations develop at $(\nabla Te \nabla n) < 0$. This occurrence must be taken into account when

considering experiments with a laser plasma magnetized in an applied magnetic field. It is emphasized that the inequality $\ell/a > \sqrt{m/M}$ is satisfied automatically in the thermally conductive region of a laser plasma, if heat propagates inward.

Burunov, Ye. A., G. M. Malyshev, G. T. Razdobarin, and V. V. Semenov. Investigating a laser spark plasma by a dispersion method using an image converter. ZhTF, no. 1, 1974, 113-118.

In the present paper, the experimental absolute values of the electron concentration n_e in a laser spark center, and radial distribution of n_e at different times within 1.5 to 60 μsec. interval, are given. The experimental assembly using a laser radiation scattering technique is described. Scattered radiation of a 1j ruby laser emitting 30 nsec pulses at $\lambda = 6943Å$ was recorded photographically with an image converter during a single pulse emission. Two scanning lasers synchronized with the spark-generating laser were focused on the spark.

The standard and shadow photographs of the scattered laser radiation show that radiation from the spark center is scattered by the plasma in direct proportion to n_e. The latter starts to decrease rapidly at distances up to 2 mm from the spark center, the distance x depending on time t of the sweep (Fig. 1). At t = 50 μsec., n_e decreases sharply and the plasma-scattered radiation becomes 1/3 as intense as Rayleigh scattering in air. Subsequent increase in scattering intensity is due to scattering by shock wave propagation in air.

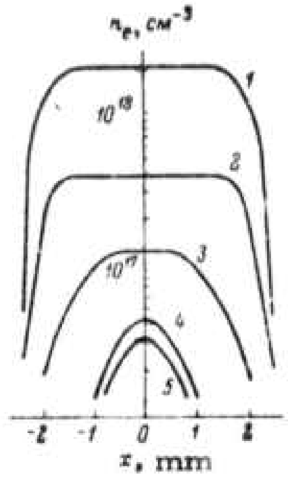


Fig. 1. Radial distribution of electron concentration in a laser spark plasma.

t, (μsec): 1.5 (1), 2.7 (2), 9.5 (3), 50 (4), and 60 (5).

At the spark center, n_e decreases by about two orders of magnitude, from 2×10^{18} to 3×10^{16} cm^{-3}, in the interval from 1.5 to 60 μsec. (Fig. 2). The decrease in n_e between 3 and 60 μsec. is described by $n \sim t^{-0.7}$ with good approximation. The initial rapid decrease and subsequent slower drop in n_e are explained by the initial high recombination rate and by the combined effect of recombination plus radial dispersion of the plasma. Recombination is the most intensive at the plasma boundary. The estimated error of the absolute n_e value determination is about 20%.

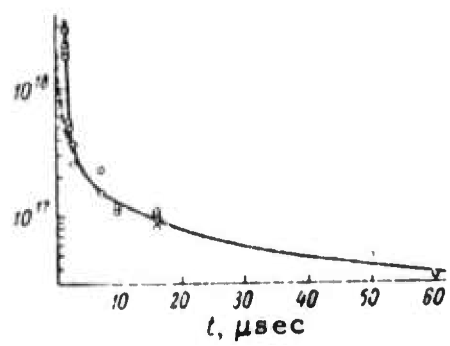


Fig. 2. Time dependence of electron concentration in the center of laser spark plasma.

Makhankov, V. G., and V. N. Tsytovich. Anomalous heating of dense plasma by laser radiation. Phys. scr., v. I, no. 5, 1973, 234-240. (RZhF, 11/73, no. 11G137). (Translation)

A range of plasma parameters is determined, within which anomalous heating due to collective processes becomes effective. Conditions are indicated for generation of oscillations at frequencies above or below the frequency of pair collisions. The effective frequencies of anomalous heating are correlated with the incident radiation energy, temperature, and density of the plasma.

Aglitskiy, Ye. V., V. A. Boyko, L. A. Vaynshteyn, S. M. Zakharov, O. N. Krokhin, U. I. Safronov, and G. V. Sklizkov. Transitions from doubly excited states of the He- and Li-like multiply charged ions (Observation in laser plasma and calculations). Preprint no. 113, Institute of Physics, AN SSSR, Moscow, 1973, pp. 61. (RZhF, 1/74, no. 1G101). (Translation).

A spectroscopic study of a laser plasma was made with sharp focusing of incident radiation to $\sim 10^{14}$ w/cm^2 power density. The plasma electron temperature was 1 keV. Formation was observed of multiply charged ions, e.g., Fe XXII-FeXXIV, with ionization potential of several keV. The experimental assembly included an Nd laser, a vacuum chamber, and an x-ray single-crystal spectrometer. Scanning spectra of Mg and Al laser plasmas in the 0.5-12Å wavelength range were obtained with the use of a convex-crystal spectrometer. The spectra featured longwave

satellite resonance lines of the Li- and He-like Mg^+ and Al^+ ions. Calculations show that the cited lines represent transitions from doubly excited levels of the He- and Li-like ions. Complete tables are given of the wavelengths, probabilities of radiative transitions, and radiationless decay on account of autoionization from doubly excited levels of the He- and Li-like ions with Z = 6 to 28. The theory of electrostatic interaction perturbations was applied to calculations. The data thus obtained can be useful for laser plasma diagnostics, e.g., temperature measurement and establishment of the ionization equilibrium mechanism.

Goncharov, V. K., L. Ya. Min'ko, Ye. L. Tyunina, and A. N. Chumakov. Experimental study of heating a low-temperature erosive laser plasma during gas dynamic propagation. ZhPMTF, no. 1, 1974, 13-18.

The gas dynamic structure and optical characteristics of erosive laser plasma flares were determined, under conditions of laser radiation propagating through the plasma normally and axially to the flare axis. In the experiments, an Nd glass laser was used with 150j output energy in 1 μsec pulses, with 1/3 duty cycle for a total 700 μsec irradiation time. The plasma was formed by radiation focusing on a ~2 mm diam. brass wire enclosed in a quartz tube with I. D. = 2 mm to limit dispersion of the plasma. Radiation power density was $\sim 10^7$ w/cm^2, with allowance for the duty cycle. The gas dynamic structure of the plasma jets was determined at atmospheric pressure from high-speed photographic recordings of the dispersion. Analysis of the time sweep and calculated parameters of the jets shows a sequence of shock waves propagating behind a stationary shock wave at a rate higher than the plasma bunches. The waves formed during laser beam propagation from above (axially) have an amplitude higher than those generated by a beam normal to the jet. This experimental fact is attributed to a partial absorption of laser radiation.

Results show that radiation attenuation depends on the duty cycle of the plasma bunches and on dispersion conditions; radiation absorption by the plasma may lead to a complete shielding of the surface. Longitudinal emission spectra of plasma jets interacting with axial laser radiation display a jump in luminous intensity at the same time as compression shock occurs. Intensity of the spectral continuum and lines peaks at the exit from the quartz tube decrease sharply further along the jet, then increase somewhat in the shock wave. Plasma temperature distribution along the jet formed during laser beam counter propagation (Fig. 1) follows the same pattern. The T peaks at the exit from the quartz

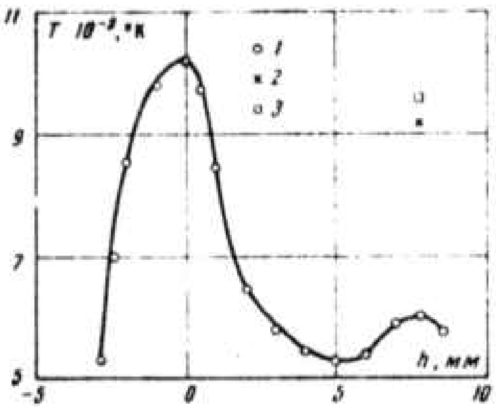


Fig. 1. Temperature profile of plasma jet with axial laser beam propagation.

1 - luminance T, 2 and 3 - T in a shock wave calculated from the measured coefficient of continuum emission and electron concentration.

tube and in a shock wave are correlated with plasma heating by the incident laser beam. The T peak indicates the effect of surface shielding from laser radiation.

Zakharov, V. P., and I. M. Protas. Mass spectrometer study of ion emission from complex materials vaporized by interaction with laser radiation. IAN SSSR. Ser. fiz, no. 2, 1974, 238-243.

Results are presented of mass spectrometric analysis of ionized vapors produced by interaction of laser radiation with A^3B^5 and A^4B^6 semiconductor single crystals, $A_2^5B_3^6$ semiconductor compounds, $NiO \cdot Fe_2O_3$ and $Y_2O_3 \cdot (Fe_2O_3)_5$ ferrites, ABO_3 titanate and rutile ceramics, and Me-Sb-S-I chalcogenide glasses. The study was designed to get a general idea about the mechanism of thin film deposition on a substrate by laser-induced vaporization of the above cited bulk materials. The laser mass spectrometer was composed of a high-resolution mass spectrometer with a special ion source and a free-running ruby laser (λ = 6943Å) emitting 800-1000 μsec pulses with 3-5 j energy. An additional h.f. ion source was used to detect particles predominant in neutral vapors.

Typical mass spectra of the cited material vapors are shown. The quantitative difference observed between mass spectra of GaAs and GaP is explained in terms of two different vaporization mechanisms as well as different thermophysical properties of As_n and P_n ions. Apparently a phase transition occurs during GaAs vaporization from a thin, highly absorbing surface layer. Expansion from heat pressure is probably the predominant mechanism of GaP vaporization with bond breaking. It is concluded from the mass spectra of GeTe and GeSe that the mechanisms of their vaporization are similar; the same conclusion holds for As_2S_3, As_2Se_3, and AsSe compounds, which vaporize mostly as molecules composed of different atoms.

The compound $NiO \cdot Fe_2O_3$ forms on a substrate by deposition of the component atoms and crystallizes as a solid solution. The Y ferrite condensate forms by a different mechanism owing to the presence of partly dissociated products (YO, FeYO) in its vapors. The mechanism of vaporization of all titanates and TiO_2 is the same, because their mass spectra are qualitatively similar.

Theoretically, deposition of ABO_3 thin films by the laser method is feasible, since the products of partial dissociation were detected in vapors of ABO_3. The same is true for amorphous thin films of the chalcogenide glasses. These films form by condensation of the structural groups, MeS, MeI, SbS_n, SbI, SbSI, etc. which are present in the vapor. Practical applicability of the laser vaporization method is confirmed by agreement between physical properties of the glass films and the original glassy systems.

Rupasov, A. A., G. V. Sklizkov, V. P. Tsapenko, and A. S. Shikanov. Studying the reflection of laser radiation from a dense plasma. ZhETF, v. 65, no. 5, 1973, 1898-1904.

Results are described of experimental investigations on reflection of laser radiation from plasma, formed during focusing of plane-polarized neodymium glass laser radiation ($\lambda = 1.06\ \mu$) on targets of various atomic numbers, at flux densities 5×10^{10}-5×10^{12} w/cm^2. The experimental setup is shown in Fig. 1. Laser pulse duration = 4 nsec, pulse rise time, 1.5 nsec; beam diameter arriving at the focusing lens (f = 5 cm) was 1.5 cm, and maximum angle θ_{max} of radiation incident on the target was 9^o. Targets used were solid specimens of Be, Al, Cu, Zn, Ta, Pb, and also Al foils and $(CH_2)_n$ foils of various thickness. Incident energy was varied

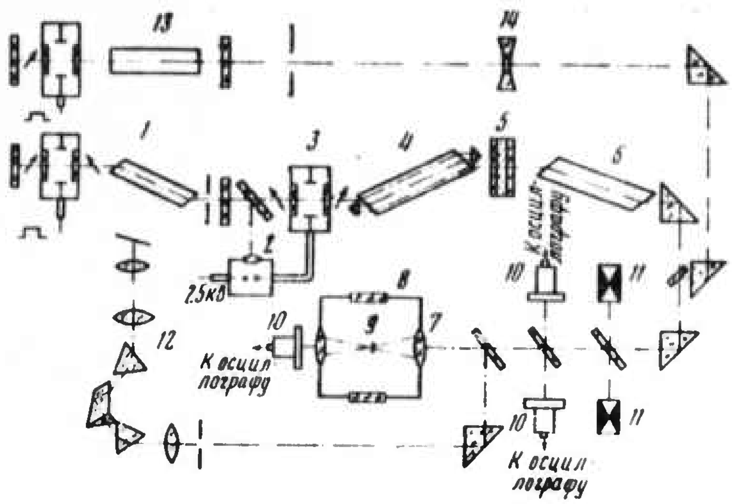


Fig. 1. Sketch of Experiment.

1- Glass laser; 2- discharger with laser ignition; 3- Kerr cell; 4- first amplifier; 5- dye cell; 6- second amplifier; 7- focusing lens; 8- vacuum chamber; 9- target; 10- coaxial photocell (FEK-09 FEK-15); 11- calorimeter; 12- prism spectrograph, 13- ruby laser; 14- negative lens for compensating chromatic aberration of focusing lens.

over a wide range with calibrated neutral light filters, which did not alter the space-time parameters of the radiation.

Relationships were determined for reflection coefficient and radiant energy of the plasma (Figs. 2, 3, 4, 5). It was found that during a change of flux density from $3x10^{10}$ up to $7x10^{11}$ w/cm^2, reflection coefficient decreased as $R \sim \Phi^{-0.2}$, after which R began decreasing anomalously fast. Beginning with a flux density $\Phi = 5x10^{11}$ watt/cm^2 for all specimens tested, a line of wavelength $\lambda = 0.53\ \mu$ was recorded in the radiation spectrum reflected back into the lens, corresponding to the second harmonic of incident radiation; the half-width of the 0.53μ line equalled ~10Å. A ruby laser ($\lambda = 0.69\mu$) was used in synchronism with the neodymium laser for measuring reflection coefficients at another wavelength;

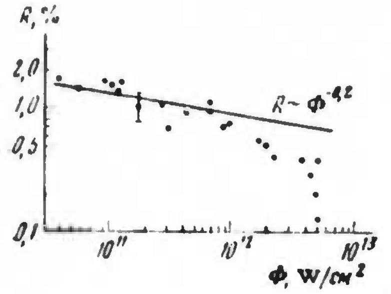


Fig. 2. Relationship of integral reflection coefficient $R = E_{ref}/E_{inc}$ as a function of flux density $\Phi = w/st_o$ for Al-target (W - laser energy)

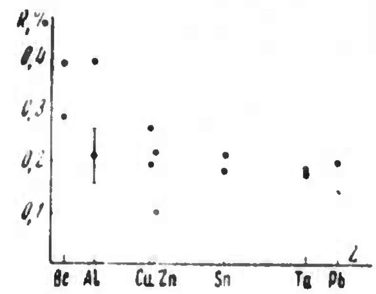


Fig. 4. R as a function of atomic number of the target at $\Phi = 5x10^{12}$ watt/cm^2.

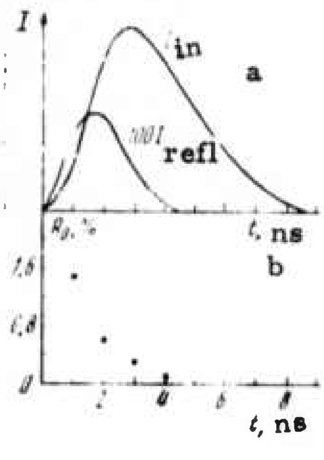


Fig. 3. Time dependence at $\Phi = 5x10^{12}$ watt/cm^2: a) Incident and reflected pulses; b) Transient reflection coefficient R_o.

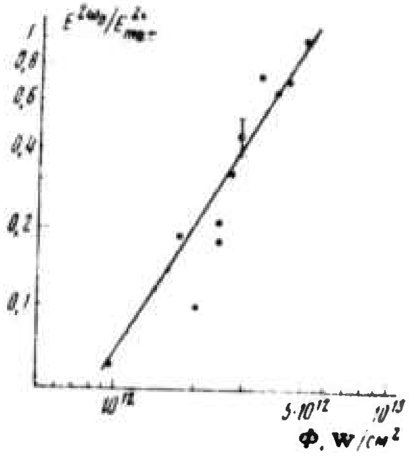


Fig. 5. Radiant energy of plasma at $\lambda = 0.53\mu$ as a function of Φ.

the probing radiation in this case was focused also in the same focal spot as that of Nd-laser. Detail discussions are given of the obtained results.

Bunkin, F. V., and V. V. Savranskiy. Optical breakdown of gases, initiated by thermal explosion of suspended macroscopic particales. ZhETF, v. 65, no. 6, 1973, 2185-2195.

A mechanism is proposed for the optical breakdown of gases by thermal explosion of suspended macroparticles in them, and a theoretical study is made of this process. Thermal explosion is defined as occurring when the total energy absorbed by particles during their inertial confinement in the vapor state, a/U_s (a = linear dimension of particles; U_s - acoustic velocity of vapors at temperatures close to critical temperature T_{cr} of the particle substance), exceeds evaporation energy of particles $\varrho qv = N_p q_1 V$ (V- volume of particles; ϱ- mass density N_p - number of atoms; q and q_1 - evaporation heat of particle substance per unit mass and unit particle, respectively).

It is shown that the mechanism in question is evidently the main process for initiating breakdown of gases in the far IR, particularly at $\lambda = 10.6\ \mu$. Based on the above results, a series of previously ambiguous experimental data on gas breakdown by CO_2 lasers are explained both qualitatively and quantitatively. Conditions are discussed under which the proposed mechanism of breakdown initiation may also play a role in the visible and near IR regions.

Experiments were conducted to observe these effects on initiation of air breakdown at $\lambda = 1.06\ \mu$ with laser pulse duration $\tau = 100$ nsec. Highly absorbing carbon black particles were introduced into the focal region. Laser beam divergence $\varphi = 10^{-3}$ rad and beam diameter was 1.5 cm; focal distance of the lens $F = 10$ cm. Volume of the focal region formed $V \gtrsim 2\text{x}10^{-6}\ \text{cm}^3$. The density of the soot particles apparently fulfilled the condition $Vn >> 1$, where n = average density of macroparticles irrespective of their dimensions. In clean air for example, breakdown occurred at a pulse energy of 0.55 j, while in the presence of soot the threshold energy was found to be less than $5\text{x}10^{-2}$ joule.

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7. SOURCE ABBREVIATIONS

AiT	-	Avtomatika i telemekhanika
APP	-	Acta physica polonica
DAN ArmSSR	-	Akademiya nauk Armyanskoy SSR. Doklady
DAN AzSSR	-	Akademiya nauk Azerbaydzhanskoy SSR. Doklady
DAN BSSR	-	Akademiya nauk Belorusskoy SSR. Doklady
DAN SSSR	-	Akademiya nauk SSSR. Doklady
DAN TadSSR	-	Akademiya nauk Tadzhikskoy SSR. Doklady
DAN UkrSSR	-	Akademiya nauk Ukrainskoy SSR. Dopovidi
DAN UzbSSR	-	Akademiya nauk Uzbekskoy SSR. Doklady
DBAN	-	Bulgarska akademiya na naukite. Doklady
EOM	-	Elektronnaya obrabotka materialov
FAiO	-	Akademiya nauk SSSR. Izvestiya. Fizika atmosfery i okeana
FGiV	-	Fizika goreniya i vzryva
FiKhOM	-	Fizika i khimiya obrabotka materialov
F-KhMM	-	Fiziko-khimicheskaya mekhanika materialov
FMiM	-	Fizika metallov i metallovedeniye
FTP	-	Fizika i tekhnika poluprovodnikov
FTT	-	Fizika tverdogo tela
FZh	-	Fiziologicheskiy zhurnal
GiA	-	Geomagnetizm i aeronomiya
GiK	-	Geodeziya i kartografiya
IAN Arm	-	Akademiya nauk Armyanskoy SSR. Izvestiya. Fizika
IAN Az	-	Akademiya nauk Azerbaydzhanskoy SSR. Izvestiya. Seriya fiziko-tekhnicheskikh i matematicheskikh nauk

IAN B	-	Akademiya nauk Belorusskoy SSR. Izvestiya. Seriya fiziko-matematicheskikh nauk
IAN Biol	-	Akademiya nauk SSSR. Izvestiya. Seriya biologicheskaya
IAN Energ	-	Akademiya nauk SSSR. Izvestiya. Energetika i transport
IAN Est	-	Akademiya nauk Estonskoy SSR. Izvestiya. Fizika matematika
IAN Fiz	-	Akademiya nauk SSSR. Izvestiya. Seriya fizicheskaya
IAN Fizika zemli	-	Akademiya nauk SSSR. Izvestiya. Fizika zemli
IAN Kh	-	Akademiya nauk SSSR. Izvestiya. Seriya khimicheskaya
IAN Lat	-	Akademiya nauk Latviyskoy SSR. Izvestiya
IAN Met	-	Akademiya nauk SSSR. Izvestiya. Metally
IAN Mold	-	Akademiya nauk Moldavskoy SSR. Izvestiya. Seriya fiziko-tekhnicheskikh i matematicheskikh nauk
IAN SO SSSR	-	Akademiya nauk SSSR. Sibirskoye otdeleniye. Izvestiya
IAN Tadzh	-	Akademiya nauk Tadzhiksoy SSR. Izvestiya. Otdeleniye fiziko-matematicheskikh i geologo-khimicheskikh nauk
IAN TK	-	Akademiya nauk SSSR. Izvestiya. Tekhnicheskaya kibernetika
IAN Turk	-	Akademiya nauk Turkmenskoy SSR. Izvestiya. Seriya fiziko-tekhnicheskikh, khimicheskikh, i geologicheskikh nauk
IAN Uzb	-	Akademiya nauk Uzbekskoy SSR. Izvestiya. Seriya fiziko-matematicheskikh nauk
IBAN	-	Bulgarska akademiya na naukite. Fizicheski institut. Izvestiya na fizicheskaya institut s ANEB
I-FZh	-	Inzhenerno-fizicheskiy zhurnal

IiR	-	Izobretatel' i ratsionalizator
ILEI	-	Leningradskiy elektrotekhnicheskiy institut. Izvestiya
IT	-	Izmeritel'naya tekhnika
IVUZ Avia	-	Izvestiya vysshikh uchebnykh zavedeniy. Aviatsionnaya tekhnika
IVUZ Cher	-	Izvestiya vysshikh uchebnykh zavedeniy. Chernaya metallurgiya
IVUZ Energ	-	Izvestiya vysshikh uchebnykh zavedeniy. Energetika
IVUZ Fiz	-	Izvestiya vysshikh uchebnykh zavedeniy. Fizika
IVUZ Geod	-	Izvestiya vysshikh uchebnykh zavedeniy. Geodeziya i aerofotos''yemka
IVUZ Geol	-	Izvestiya vysshikh uchebnykh zavedeniy. Geologiya i razvedka
IVUZ Gorn	-	Izvestiya vysshikh uchebnykh zavedeniy. Gornyy zhurnal
IVUZ Mash	-	Izvestiya vysshikh uchebnykh zavedeniy. Mashinostroyeniye
IVUZ Priboro	-	Izvestiya vysshikh uchebnykh zavedeniy. Priborostroyeniye
IVUZ Radioelektr	-	Izvestiya vysshikh uchebnykh zavedeniy. Radioelektronika
IVUZ Radiofiz	-	Izvestiya vysshikh uchebnykh zavedeniy. Radiofizika
IVUZ Stroi	-	Izvestiya vysshikh uchebnykh zavedeniy. Stroitel'stvo i arkhitektura
KhVE	-	Khimiya vysokikh energiy
KiK	-	Kinetika i kataliz
KL	-	Knizhnaya letopis'
Kristall	-	Kristallografiya
KSpF	-	Kratkiye soobshcheniya po fizike

LZhS	-	Letopis' zhurnal'nykh statey
MiTOM	-	Metallovedeniye i termicheskaya obrabotka materialov
MP	-	Mekhanika polimerov
MTT	-	Akademiya nauk SSSR. Izvestiya. Mekhanika tverdogo tela
MZhiG	-	Akademiya nauk SSSR. Izvestiya. Mekhanika zhidkosti i gaza
NK	-	Novyye knigi
NM	-	Akademiya nauk SSSR. Izvestiya. Neorganicheskiye materialy
NTO SSSR	-	Nauchno-tekhnicheskiye obshchestva SSSR
OiS	-	Optika i spektroskopiya
OMP	-	Optiko-mekhanicheskaya promyshlennost'
Otkr izobr	-	Otkrytiya, izobreteniya, promyshlennyye obraztsy, tovarnyye znaki
PF	-	Postepy fizyki
Phys abs	-	Physics abstracts
PM	-	Prikladnaya mekhanika
PMM	-	Prikladnaya matematika i mekhanika
PSS	-	Physica status solidi
PSU	-	Pribory i sistemy upravleniya
PTE	-	Pribory i tekhnika eksperimenta
Radiotekh	-	Radiotekhnika
RiE	-	Radiotekhnika i elektronika
RZhAvtom	-	Referativnyy zhurnal. Avtomatika, telemekhanika i vychislitel'naya tekhnika
RZhElektr	-	Referativnyy zhurnal. Elektronika i yeye primeneniye

RZhF	-	Referativnyy zhurnal. Fizika
RZhFoto	-	Referativnyy zhurnal. Fotokinotekhnika
RZhGeod	-	Referativnyy zhurnal. Geodeziya i aeros"-yemka
RZhGeofiz	-	Referativnyy zhurnal. Geofizika
RZhInf	-	Referativnyy zhurnal. Informatics
RZhKh	-	Referativnyy zhurnal. Khimiya
RZhMekh	-	Referativnyy zhurnal. Mekhanika
RZhMetrolog	-	Referativnyy zhurnal. Metrologiya i izmeritel'naya tekhnika
RZhRadiot	-	Referativnyy zhurnal. Radiotekhnika
SovSciRev	-	Soviet science review
TiEKh	-	Teoreticheskaya i eksperimental'naya khimiya
TKiT	-	Tekhnika kino i televideniya
TMF	-	Teoreticheskaya i matematicheskaya fizika
TVT	-	Teplofizika vysokikh temperatur
UFN	-	Uspekhi fizicheskikh nauk
UFZh	-	Ukrainskiy fizicheskiy zhurnal
UMS	-	Ustalost' metallov i splavov
UNF	-	Uspekhi nauchnoy fotografii
VAN	-	Akademiya nauk SSSR. Vestnik
VAN BSSR	-	Akademiya nauk Belorusskoy SSR. Vestnik
VAN KazSSR	-	Akademiya nauk Kazakhskoy SSR. Vestnik
VBU	-	Belorusskiy universitet. Vestnik
VNDKh SSSR	-	VNDKh SSSR. Informatsionnyy byulleten'
VLU	-	Leningradskiy universitet. Vestnik. Fizika, khimiya
VMU	-	Moskovskiy universitet. Vestnik. Seriya fizika, astronomiya

ZhETF	-	Zhurnal eksperimental'noy i teoreticheskoy fiziki
ZhETF P	-	Pis'ma v Zhurnal eksperimental'noy i teoreticheskoy fiziki
ZhFKh	-	Zhurnal fizicheskoy khimii
ZhNiPFiK	-	Zhurnal nauchnoy i prikladnoy fotografii i kinematografii
ZhNKh	-	Zhurnal neorganicheskoy khimii
ZhPK	-	Zhurnal prikladnoy khimii
ZhPMTF	-	Zhurnal prikladnoy mekhaniki i tekhnicheskoy fiziki
ZhPS	-	Zhurnal prikladnoy spektroskopii
ZhTF	-	Zhurnal tekhnicheskoy fiziki
ZhVMMF	-	Zhurnal vychislitel'noy matematiki i matematicheskoy fiziki
ZL	-	Zavodskaya laboratoriya

8. AUTHOR INDEX